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E-706

March 30, 1984

Dr. Frederick Lobkowicz
Professor of Physics
University of Rochester
Department of Physics & Astronomy
River Campus Station
Rochester, New York 14627

Subject: Univ. of Rochester P.O. U-17288 (CCI #584)
Failure Mode Analysis / LAC Cryostat

Dear Dr. Lobkowicz:

The failure mode analysis for the LAC cryostat is enclosed for your review. This analysis considered the following possible occurrences:

(1) Insulation failure.
(2) Dewar rupture.
(3) Dewar overfill.
(4) Power failure.
(5) Transfer line failure.
(6) Cooling of the upper shell.
(7) Hydrogen cylinder failure.

This analysis addresses the major LAC cryostat operating concerns and suggests features to be incorporated in the design and precautions to be observed during operation.

Every attempt was made to make this analysis all inclusive. However, we recognize that one or more items of concern to you may have been overlooked, and as such, your comments and suggestions are solicited.

Sincerely yours,

CRYOGENIC CONSULTANTS, INC.

Jerry B. Gibbs

Jerry B. Gibbs

JBG/mm

Encls. -Failure Mode Analysis / LAC Cryostat (w/Calculations)

cc: T. E. Kranyecz w/Encls.
P. C. Vander Arend w/Encls.

FAILURE MODE ANALYSIS / LAC CRYOSTAT

PREPARED UNDER P.O. U-17288 BY
CRYOGENIC CONSULTANTS, INC.
ALLENTOWN, PA

FOR

UNIVERSITY OF ROCHESTER
ROCHESTER, NY

March 30, 1984

DEWAR INSULATION FAILURE

Steady state heat leak to the dewar (Table I) through (1) the insulated walls, (2) the dewar wall, (3) the top plate, and (4) the support rods and vent line will be approximately 1,760 W and will be continuously removed from the system via the nitrogen cooled Ar recondensing coil. In this manner, the system pressure will be maintained at 15-16 psia. Two safety relief devices, (1) a relief valve set at 7.5 psig, and (2) a rupture disc set at 12 psig, are provided to guard against overpressurization which can occur as the result of increased heat leak to the dewar or loss of LIN in the Ar recondensing coil. The former is most likely to occur as a result of a loss of insulation surrounding the dewar.

TABLE I

Steady State Heat Leak to Dewar

	Heat Leak
Insulated Walls and Bottom:	1,350 W
Dewar Wall:	370 W
Top Plate:	25 W
Support Rods and Vent Line:	15 W
	1,760 W

The dewar will be insulated with 12 in. of fiberglass insulation protected and held in place with a rubber or heavy plastic "bag" secured at the top of the vessel. A nitrogen purge of the insulation will maintain a slight positive pressure in the "bag" and prevent the infiltration of air into the insulating barrier. The heat leak through the dewar insulation during steady state amounts to 1,350 W total or 1.1 W/ft^2 of insulated surface area.

An insulation failure over 10% of the surface area resulting in heat leak through this area of 46,900 W (160,000 Btu/hr) was assumed. The calculation of an insulation failure heat leak is a complicated task requiring many iterations for a number of different assumptions regarding: (1) degree of insulation failure, (2) external convection currents,

(3) controlling thermal resistances, (4) boiling coefficients, etc. A simplified approach was employed to attempt to establish a worst case. If the vapor insulation barrier were reduced from a thickness of 12 in. to 1 in., then heat leak would increase to 14.7 W/ft^2 (50 Btu/hr ft^2), the vapor barrier being the controlling resistance. If the barrier were further reduced to 0.1 in., the vapor barrier would still be controlling and the heat leak would be of the order of 147.0 W/ft^2 (500 Btu/hr ft^2). An insulation failure of this magnitude over 10% of the surface area (120 ft^2) would produce a heat leak of 147.0 W/ft^2 x 120 ft^2 = 17,600 W (60,000 Btu/hr). The value of 46,900 W (160,000 Btu/hr) was chosen to be conservative, and the following analysis is based on this figure.

Pressure would gradually increase in the dewar, and at 7.5 psig, the relief valve would open. The rate of rise to the 7.5 psig relief point would be moderated by two factors: (1) the LAr condensation coil would attempt to maintain the 15 psia set pressure by increasing LIN flow to the condensing coil, and (2) the equilibrium liquid enthalpy would be increasing with pressure. The enthalpy of saturated LAr increases by 185 J/gmole (2.0 Btu/lb) from 14.7 psia to 22.0 psia. The LAr inventory in the dewar is approximately 210,000 lbs, and if 10% or 21,000 lbs of LAr above the bare spot would equilibrate at 22.0 psia during pressure rise, 12,310 W (42,000 Btu) of heat leak would be removed representing a 16 minute time delay. If the entire 46,900 W (160,000 Btu/hr) of heat leak vaporized the LAr, the vaporization rate would be 39 lbs LAr/min., or 250 acfm of cold gas to be removed from the system. A 6 in. IPS, Schedule 5 vent pipe with relief valve will vent this flow with a pressure drop of less than 0.5 psi.

DEWAR RUPTURE

SHould the dewar rupture or develop a leak, liquid argon (LAr) will spill into the concrete pit and vaporize. The pit as presently designed is 21.0 ft in diameter, 23.25 ft in height to the shoulder, and has a volume of 8,050 ft^3. Assuming a full argon dewar and a catastropic rupture, approximately 210,000 lbs or 2,410 ft^3 of LAr would be quickly deposited in the pit. The liquid level in the pit would be 7.0 ft.

At the moment of rupture, a rapid boiling would commence in the pit and would represent the maximum vapor generation rate. As the pit walls cool, the vapor generation rate will decline. Assuming the concrete has a thermal conductivity of 1.0 Btu/lb ft °F, the vapor generation rate, G, after 35 sec (corresponds to a temperature wave penetration of 1.0 in. into the concrete) is:

$$G = \frac{q}{\Delta h \cdot \rho} = \frac{K\ A\ T}{X \cdot \Delta h \cdot \rho} = 152{,}000 \text{ acf/hr}$$

Where: K = thermal conductivity of concrete, 1.0 Btu/lb ft hr

A = Surface area for heat transfer, 800 ft^2

X = Thickness, 0.083 ft = 0.1 in.

ΔT = Temperature driving force, 383°F

Δh = LAr heat of vaporization, 70 Btu/lb

ρ = Ar density, 0.360 lbs/ft^3

Table II shows the progress of the temperature wave penetration into the concrete, the corresponding vaporization rates, and the cumulative amount of LAr vaporized.

Although there will be an initial surge of gas generated, the pit quickly takes on the characteristics of an inground storage tank, and the gas generation rate decreases rapidly. At time θ = 337 min. (5.6 hrs) from rupture, only 42,000 lbs of the 210,000 lbs of argon originally in the dewar have been vaporized by heat leak through the pit walls.

DEWAR RUPTURE (contd.)

TABLE II

LAr Vaporization Data

X_1 Inches	θ_1 Minutes	Vapor Rate Lbs/Hr	Cumulative LAr Vaporized Lbs
0.5	.023	263,700	1,940
1.0	.58	54,700	3,420
2.0	2.3	26,400	4,600
3.0	5.2	17,600	5,660
4.0	9.4	13,200	6,730
5.0	14.5	10,500	7,740
24.0	337.0	2,200	42,000

The vaporized LAr is dense, 0.36 lbs/ft^3 at -300°F and 0.103 lbs/ft^3 at 70°K. The vapor generated will stratify above the liquid and further "insulate" the exposed liquid surface from heat exchange with the air in the room.

Once the LAr has dumped into the pit, there will be approximately 5,700 ft^3 of void volume in the pit above the liquid level. Assuming a uniform Ar vapor density of 0.36 lbs/ft^3 (at 1.0 atm, -300°F), this volume can accommodate only 2,050 lbs of vapor which will be generated in less than 0.5 minutes. Thereafter the cold vapor will spill over onto the floor, exiting the pit at a velocity of 7 ft/min at a vapor generation rate of 55,000 lbs/hr.

The major safety concerns associated with a LAr release is the possible asphyxiation of personnel working in a closed area and low temperature "burns". Precautions to preclude these occurrences will have to be taken. The pit will suffer damage as a result of thermal contraction during a dewar rupture and will have to be repaired. It may be desirable to incorporate in the pit means to recover LAr from the pit and return it to the storage tank after which it could be purified and reused. From the previous analysis, it should be possible to recover a substantial portion of the LAr spilled.

LAR DEWAR OVERFILL PROTECTION

When filling the LAr dewar from storage, there is the possibility that the vessel could be overfilled exposing the carbon steel upper shell and flange to low temperatures. Although heaters are provided on the flange, they may not be able to provide enough heat in the case where the LAr level reached the flange. To guard against this occurring, several precautions should be implemented. Liquid level probes, ΔP cells, and pressure alarms should be installed in the dewar.

A liquid level probe should be provided for normal operation to indicate when the liquid level reaches the desired height; i.e., covers the top of the Hadron Detector. A ΔP cell set to alarm at a liquid level 2 ft below normal operating level will warn the operator that the dewar is nearly full. A second ΔP setting at 1 ft above normal liquid level should be provided to: (1) sound an alarm, (2) close the valve at the pump discharge, and (3) turn off the pump to prevent further filling of the dewar. Assuming the LAr transfer pump is operated at 100 gallons per minute, the dewar fill rate would be 17 min/ft of vertical height. There is a 16 in. cold gas space between the top of the Hadron Detector (normal LAr operating level) and the bottom of the fiberglass insulation layer which would require 22.6 min to fill with liquid at a pump rate of 100 gpm. Therefore, in addition to the high level alarm, there is a reasonable time delay for an operator to recognize an overfill condition and take corrective action.

The design feature whereby all top entry takeoff or fill lines are terminated in the cold gas barrier just above the normal LAr operating level provides yet another safeguard against overfill (see Figure 1). During filling, the residual vapor within the tank plus the vapor generated by cooldown less that recondensed will exit the dewar via one of these lines. If the liquid level continues to rise above the top of the Hadron Detector, it will shortly seal off the vapor vent and cause pressure to rise in the dewar. Pressure alarms should be provided to shut off the pump and close the pump discharge valve when the pressure in the dewar reaches 5 psig.

The analysis to this point has assumed LAr transfer from storage to the dewar is via a pump. In the event this transfer is accomplished using pressure generated in the storage tank, the safety interlocks would be on the control valve regulating the flow into the LAr tank and possibly the valve regulating the LAr vaporizer on the storage tank.

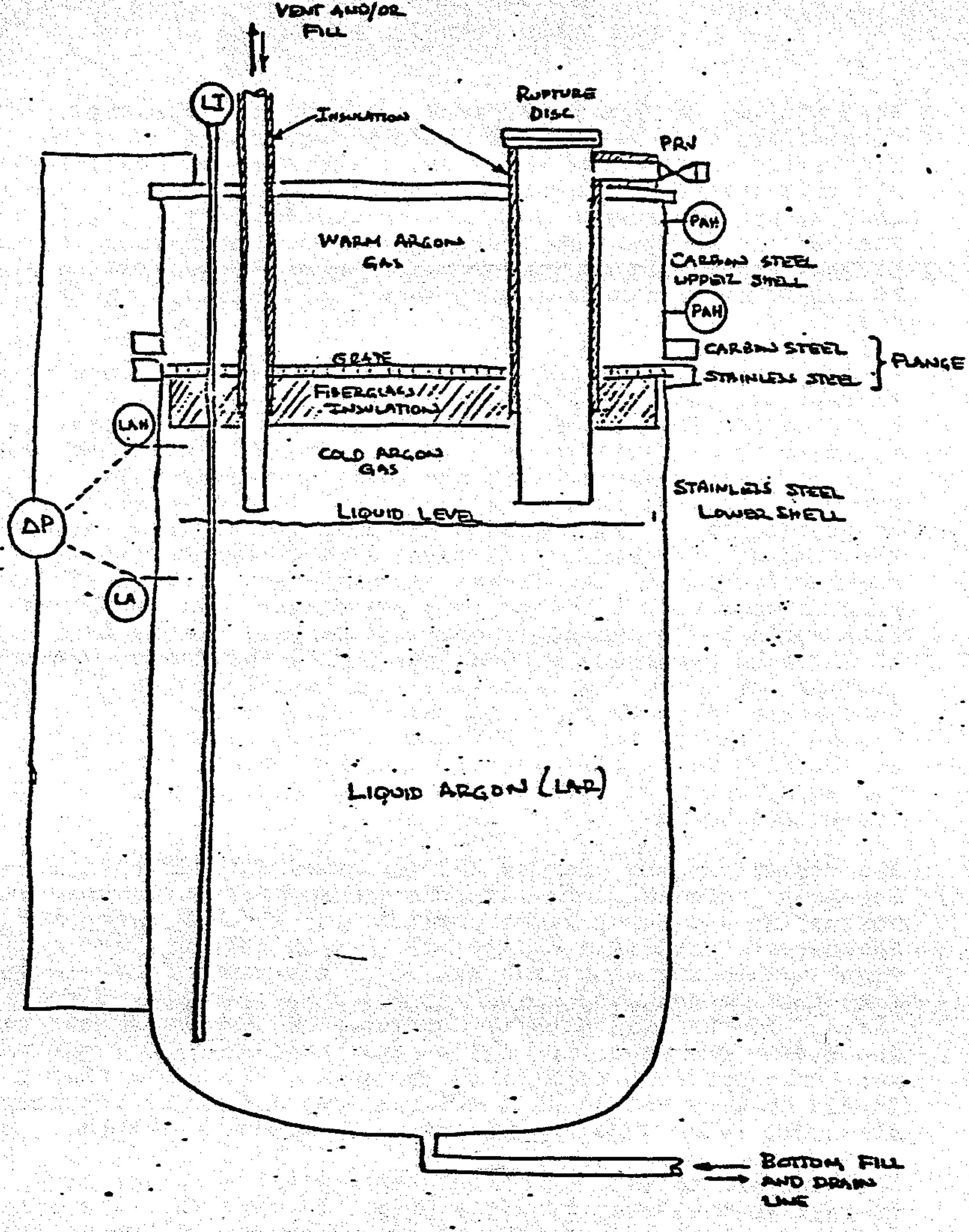


FIGURE 1

SIMPLIFIED SKETCH OF THE LAR DEWAR SHOWING LOCATION OF VENT, FILL AND PRESSURE RELIEF LINES RELATIVE TO LAR LIQUID LEVEL DURING NORMAL OPERATION

UPPER SHELL COLD TEMPERATURE PROTECTION

The top plate on the dewar is fabricated of carbon steel and must not be allowed to get cold. To prevent this from happening a blanket of fiberglass insulation 32 in. thick and a 59 in. stagnant argon gas space have been provided above the liquid argon. The pressure relief line will extend through this insulation into the cold gas space between the LAr and the insulation barrier to prevent convention currents from developing in the warm stagnant argon gas barrier during pressure relief. That is, in the event of a dewar insulation failure or loss of LN_2 to the LAr recondenser resulting in vessel overpressurization, the vapor venting will occur in the cold Ar gas space above the LAr surface rather than from the stagnant argon gas layer above the insulation barrier. This will prevent cold gas from entering this stagnant argon gas layer and will assure that the top plate stays warm.

The vent line is insulated from 12 in. above the top plate to 24 in. into the fiberglass insulation barrier with 1 in. of fiberglass insulation to prevent cooling of the top plate when cold gas is being vented. Under these conditions, the heat leak from the plate to the cold gas which is venting is insignificant relative to the thermal mass of the plate.

The lower shell and mating flange are constructed of stainless steel and can be subjected to temperatures of -300°F without risk of failure. This, however, is not the case with the upper shell and flange which are constructed of carbon steel and which must be protected from temperatures below -20°F. Heat transfer from ambient through the lower shell to LAr temperatures of -300°F could result in temperatures in the upper mating flange dropping below 32°F. Frost would then form, insulating the flange from ambient and resulting in an even lower temperature occurring. Below -20°F structural damage could occur. Under normal operating conditions, the heat leak from the flange to the -303°F sink would be of the order of 370 W. The installation of four thermostat controlled heaters each rated at 500 W spaced equidistant around the circumference of the flange will provide adequate protection for the carbon steel flange in the event heat leak is increased due to an upset.

POWER FAILURE

A general power failure during normal operation; i.e., when the dewar is full and either in a standby mode or under test conditions will not pose any immediate danger to the LAr system. The LIN to recondenser instrumentation in both the dewar and LAr storage tank is pneumatic and will continue to operate properly as long as instrument air is available. The electric resistance strip heaters mounted on the carbon steel upper flange will, of course, not operate posing a risk of overcooling this flange. The heat lost through the flange to the liquid argon via the lower vessel wall is normally of the order of 375 W, and any cooling of this flange will occur over a period of time; i.e., there is no immediate danger. However, power should be restored to these heaters, and this power could be provided with a backup generator which would also provide emergency power to operate instrumentation and valves. A low temperature alarm located on the upper flange would serve to warn the operator any time there exists a danger of overcooling this flange.

A power failure during LAr transfer will affect the pump, the liquid level gauge, ΔP cells, and the pump discharge valve as follows:

-The pump will shut off.

-The discharge valve will close.

-The liquid level instrumentation will be inoperable.

None of these occurrences will pose any immediate danger to the system. However, again the upper flange heaters will need to be supplied with emergency power as described above.

A power failure (or mechanical failure) when the gantry and dewar are being moved will cause the gantry to stop abruptly causing the LAr in the dewar to surge in the direction of movement as the kinetic energy of the fluid is converted to potential energy through a rising of the liquid level. However, the danger of the liquid level approaching the carbon steel flange and upper shell is nil. The gantry will move at a maximum velocity of 0.25 cm/sec, and if the dewar contains 210,000 lbs of LAr (normal operating charge), the fluid will possess a kinetic energy of

POWER FAILURE (contd.)

0.05 dynes/cm^2. This converts to a head of only 3×10^{-5} cm of LAr. There is a clearance between the liquid level and the bottom of the fiberglass insulation shield of 18 in. (see Figure 1, LAr Dewar Overfill Protection Section).

TRANSFER LINE FAILURE

Transfer of LAr from the LAr storage tank to the dewar can be accomplished using either the LAr pump or the pressure building coil to pressurize the storage tank. LAr can also be transferred directly from the purifier to either the storage tank or the dewar. During any of these transfers, the possibility exists of a transfer line failure resulting in a LAr spill.

To get a feel for the severity of such a failure, a transfer rate of 100 gpm was assumed and a vacuum jacketed transfer line with a 2 in. IPS, Schedule 5 inner line was selected. The pressure drop in this line at 100 gpm will be 0.039 psi/ft of length.

If a line should fail, the maximum discharge rate at the point of failure is a function of the C_V of the upstream valve. Assuming a C_V of 50, the discharge rate would vary from 140 gpm to 170 gpm depending on the pressure drop across the valve. Corrective action to stop the flow of LAr would be taken by the operator(s) who should be present at all times during a LAr transfer. The hazards involved in such a spill would be: (1) asphyxiation in confined spaces, but probably not in a big open space, and/or (2) low temperature "burns". Respirators (air packs) should be readily accessible and the operators must be wearing protective clothing.

HYDROGEN CYLINDER FAILURE

The argon purification unit employs a deoxo reactor to remove trace quantities of oxygen from argon gas. The oxygen is reacted with hydrogen at ambient temperature in the presence of a platinum group catalyst. Water, the reaction product, is removed by freezing it out in the warm heat exchanger. Hydrogen for the reaction is supplied from an A-size cylinder which when full contains 263 scf of hydrogen at 2,400 psig. This cylinder of hydrogen presents a two-fold safety hazard: (1) the high pressure present in the cylinder, and (2) the flammable nature of the hydrogen. Table III presents the hydrogen gas and cylinder data:

TABLE III

Hydrogen Gas and Cylinder Data

Gas:	Hydrogen
Specific Volume @ 70°F and 1 atm:	191.96 ft^3/lb
Cylinder:	A-size
Pressure @ 70°F:	2,400 psig
Color:	Red
CGA Cylinder Valve Outlet:	350 BX540/670
Handling and Shipping Classification:	70
NFPA Rating:	Very Flammable Gas
DOT Red Label, Flammable Compressed Gas Flammable Limits:	4-75% Vol % in Air
Ignition Temperature	1,075°F
Noncorrosive	

Approximately 6,320 ft^3 of dilution air is required to mix with the 263 ft^3 of hydrogen in a full cylinder to bring the mixture below the flammable limits of hydrogen. This represents the air present in a cube 18.5 ft on a side. A cylinder rupture whereby the entire contents of the cylinder is liberated instantaneously is a highly unlikely

HYDROGEN CYLINDER FAILURE (contd.)

occurrence, particularly when the cylinder is stationary. This type of failure is more likely to occur during transport when the cylinder is being manually handled and the valve cover has not been secured to the cylinder. The attached storage and handling procedures (Attachment #1, Sheets 1 and 2), if adhered to, will reduce the risk of a cylinder accident to near zero.

A leaking cylinder is a more likely occurrence, and the leak will undoubtedly be located in the valve or regulator. Such a leak will not pose a flammable hazard, but as a general precaution, the cylinders should at all times be located away from spark sources or flames.

VACUUM JACKETED CONTROL VALVE DATA SHEET

ITEM NO.	PCV-1	PCV-2
No. Required	One (1)	One (1)
Service (Argon Recondenser)	Steady State	Cooldown
Fluid and State	LN_2	LN_2
Inlet Press. at Oper. Cond. Psia	30	30
Maximum Inlet Press. Psia	95	95
Pressure Drop at Oper. Cond. Psi	15	15
Max. Shut-Off ΔP Psi	95	95
Temperature at Oper. Cond. °F	-325	-325
Max. or Min. Temperature °F (Max)	+100	+100
Minimum Flow Oper. Cond. #/Hr	80	240
Normal Flow Oper. Cond. #/Hr	500	1500
Maximum Flow Oper. Cond. #/Hr	500	1500
C_v Req'd. (Steady State/Norm. Oper)	.28	.84
Valve C_v Desired	1.25	4
Flow Under/Over Seat	Under	Under
Body Rating (Min)	300 psig	300 psig
Connections - Body	1/2"IPS S.W.	1/2"IPS S.W.
- Vacuum Jacket		
Inner Valve - Size		
- Type		
- Characteristic	Equal %	Equal %
Materials - Body	SS 304	SS 304
- Vacuum Jacket	SS 304	SS 304
- Plug	SS304 w/Kel-F	SS304 w/Kel-F
- Seat	SS 304	SS 304
- Packing Nut	Std.	Std.
- Stem (Dia.)	Std.	Std.
Stem & Plug-Integral/Screwed & Pinned	Scr.&Pin.	Scr.&Pin.
Bonnet Extension Length	**	**
Max. Packing Leakage cc/hr STP 50	@ 95 psig P	Same
Mass Spec. Tightness Reqd. on Body	No Reading on	Lowest Scale
Topworks Operating Air Range for		
0-100% Stroke at Max. Shut-Off ΔP	6-30 psig	6-30 psig
On Air Failure - Valve to	Close	Close
Max. Heat Leak @ Oper. Temperature	2 W	2 W
Manual Operator - Side or Top Mtd.	Not Reqd.	Not Reqd.
Topworks Diameter (Research Control)	7" Ø Max.	7" Ø Max.
Face-to-Face - Valve	**	**
Stem Vacuum Jacket	2-3/8"OD **	2-3/8"OD **
Valve Serial (Model) Number		
VALVE POSITIONER (a)	Yes	Yes
Control Range Input	6-30 psig	6-30 psig
By-Pass & Gauges/Gauges Only		
Airset (a)	Not Reqd.	Not Reqd.
Lift Flow Curve	Reqd.	Reqd.

*The supplier is to furnish all information so marked.

(a) When specified, positioner and air set to be mounted and piped by Vendor.

CRYOGENIC CONSULTANTS, INC.

Date: 7/20/84

Rev.

Mfgr. and Model No.

Cryolab CV-8 Series

Spec. No. S-54-584-1

Attachment #1
Sheet 1 of 2

Storage and Handling of Specialty Gases

The following practices should be observed when gases are being handled and stored. Additional precautions may be necessary, depending upon the category to which the gas belongs (corrosive, cryogenic, high pressure, flammable, inert, oxidant, or toxic), the properties of the gas, and the process in which it is used.

General

- Only experienced and properly instructed persons should handle specialty gases.
- Refer to all state and local regulations regarding the storage of cylinders.
- Ascertain the identity of the gas before using.
- Know and understand the properties of each gas before using.
- Develop plans to cover any emergency situation that might arise.
- When doubt exists as to the correct handling procedure for a particular gas, contact the supplier.

Storage

1. Assign a definite storage area for cylinders and post it with the names of the gases stored.
2. Ascertain that an adequate supply of water is available for first aid, fire action, or dilution of corrosive material in the event of a spill.
3. Never transfer gases from one cylinder to another.
4. Do not remove or deface labels, decals, etc. provided by the supplier for the identification of the cylinders' content.
5. Protect cylinders from damage.
6. Do not subject cylinders to abnormal mechanical shocks, which may cause damage to their valves or safety devices.
7. Never attempt to repair or alter cylinder valves or safety relief devices.
8. Leave valve protection caps in place until the cylinder has been either secured against a wall or bench or placed in a cylinder stand and is ready for use.
9. Never lift a cylinder by the cap.
10. Always employ a hand truck or other suitable device for transporting cylinders, even for a short distance.
11. Do not use cylinders as rollers or supports or for any purpose other than to contain the gas received.
12. Employ appropriate pressure-regulating devices on all cylinders where the gas is being admitted to systems having pressure rating limitations lower than the cylinder pressure.
13. Ascertain that all electrical systems are suited for service as outlined in appropriate codes such as the National Fire Protection Association codes.
14. Never use direct flame or electrical heating devices to raise the pressure of a cylinder.
15. Provide a dry, well ventilated, and preferably fire-resistant storage area.
16. Protect cylinders stored in the open against rusting and extremes of weather.
17. Store cylinders away from sources of heat and ignition and never subject them to temperatures above 125°F.
18. Store empty and full cylinders separately and arrange full cylinders so that old stock is used first.
19. Separate cylinders of gases belonging to various categories, taking into account the nature of the gases.
20. Separate cylinders containing oxygen and other oxidants from flammable gases by a minimum of 20 feet or by a fire-resistant partition.
21. Store only the amount of flammable or toxic gas required for a specific application.
22. Store cylinders containing flammable gases away from other combustible materials.
23. Before entering a storage area where flammable or toxic gases are stored, conduct tests to determine whether flammable or toxic atmospheric concentrations are present.

Handling

1. Use gloves.
2. Use safety glasses, chemical goggles, or full-face shield.
3. Have available self-contained breathing apparatus or a full-face air-line respirator in the event of an emergency.
4. Never permit oil, grease, or other readily combustible substances to come in contact with oxygen or other oxidant cylinders or their valves.
5. Use soapy water or approved explosimeters to detect flammable gas leaks.

Basic Emergency Action Procedures

- Understand the properties of the product being handled.
- Develop effective emergency procedures based upon the severity of the hazard and the type of emergency that may occur.
- Train emergency crews in the proper action to be taken.

Fire Extinguishing Methods

Notify the local Fire Department about the type of flammable material being handled and the best method to use in fighting the particular kind of fire. In case of an emergency, have self-contained air breathing equipment in the work area and in adjacent uncontaminated areas. The best method to follow when escaping gas is burning is to stop the flow of gas before extinguishing the fire. If the fire is extinguished before the gas is turned off, an explosive mixture with air may be formed, which could result in more extensive damage. However, if the fire must be extinguished in order to effect an immediate shutoff of the gas supply, use carbon dioxide or dry chemical extinguishers. Cool the surrounding area with water spray in order to prevent ignition of other combustible materials.

Oxidizing and nonflammable toxic and nonflammable corrosive gases may also be in the area of or involved in a fire. Develop procedures to eliminate or minimize the hazards associated with these products. Wear self-contained breathing apparatus when fighting fires involving toxic gases and gases that decompose when heated to produce toxic fumes. Wear goggles or full protective clothing when fighting fires involving gases that are irritating or corrosive to the eyes or skin or gases that react to produce irritants or corrosives. With some gases special protective clothing must be used. Consider the physical and chemical properties (specific gravity, solubility, reactivity, etc.) of the particular gas in relation to fire fighting measures to be employed.

Handling of Leaking Cylinders

Most leaks occur at the valve used in the top of the cylinder. Areas that may be involved are:

1. valve threads
2. safety device
3. valve stem
4. valve outlet

If a leak develops, effect emergency action procedures and notify the supplier. Never attempt to repair a leak at the valve threads or safety device. Consult with the supplier for instructions if the leak is located at the valve stem or valve outlet. The following general procedures are for leaks of minimum size where the indicated action can be taken without serious exposure to personnel.

If a leak develops in a cylinder containing flammables, inerts, or oxidants, ensure that there is adequate ventilation to dissipate the gas. Move the cylinder to an isolated area (away from combustible material if a flammable or oxidizing gas) and post signs that describe the hazards and state warnings. Leaks may increase in size as the gas is released if the product is corrosive.

Some corrosives are also oxidants or flammables, adding to the seriousness of the leak. Move the cylinder to an isolated, well ventilated area and use suitable means to direct the gas into an appropriate chemical neutralizer. Post signs that describe the hazards and state warnings.

Follow the same procedure for toxic gases as for corrosive gases. Move the cylinder to an isolated, well ventilated area and use suitable means to direct the gas into an appropriate chemical neutralizer. Post signs that describe the hazards and state warnings.

When the nature of the leaking product or the size of the leak constitutes a hazard, wear self-contained breathing apparatus and/or protective clothing. Basic action for large or uncontrollable leaks should include the following steps:

1. evacuation of personnel
2. rescue of injured personnel by crews equipped with adequate personnel protective clothing and breathing apparatus
3. fire fighting action
4. emergency repair
5. decontamination

First Aid Measures

The first aid instructions given are considered to be applicable in the vast majority of cases. In all cases, a study of the particular product involved may dictate either additional or completely different first aid instructions.

If an irritating or corrosive gas comes in contact with the eyes, immediately flush the eyes with copious quantities of water for at least fifteen minutes. Call a physician. If a corrosive gas comes in contact with the skin, flush the affected area with copious quantities of water for at least fifteen minutes while removing contaminated clothing and shoes. Call a physician.

If a person inhales a toxic gas, remove the victim to fresh air. Keep the person warm and quiet. If the person is not breathing, give artificial respiration (preferably mouth-to-mouth). If breathing is difficult, have a a trained person administer oxygen. Call a physician.

If a person is overcome by an asphyxiant, remove the victim to fresh air. Keep the person warm and quiet. If breathing has ceased, apply artificial respiration (preferably mouth-to-mouth). Call a physician.

Some compressed gases are a liquid in the cylinder. When the liquid is released to atmospheric pressure, it rapidly vaporizes, absorbing large quantities of heat from the surroundings. If the liquid comes in contact with the body, it absorbs this heat from the tissue, causing "burns". In case of contact, flush the affected area gently with cold water. Call a physician.

Steady State Heat Leak

1) Heat leak through insulation surrounding the dewar.

Surface Area (incl. Bottom) = 1209 ft^2

$\Delta T = 80 - (-303) = 383°F$

$K_{N_2} = 0.00991$ Btu/hr·ft·°F (arith. average)

$$q_1 = k\frac{A\,\Delta T}{x} = 0.00991\frac{(1209)(383)}{1.0} = 4589 \text{ Btu/hr.}$$
$$= 1345 \text{ watts}$$

2) Heat leak through the lower shell walls from the flange.

$$\int_{T_1}^{T_2} k\,dT \text{ (stainless steel)} = \int_{80k}^{300k} k\Delta T = 30.6 - 4.3 = 26.3 \text{ watts/cm}$$
$$= 2737 \frac{\text{Btu}}{\text{ft}\cdot\text{hr}}$$

$t_{shell} = 9/16$ in $= 0.5625$ inches

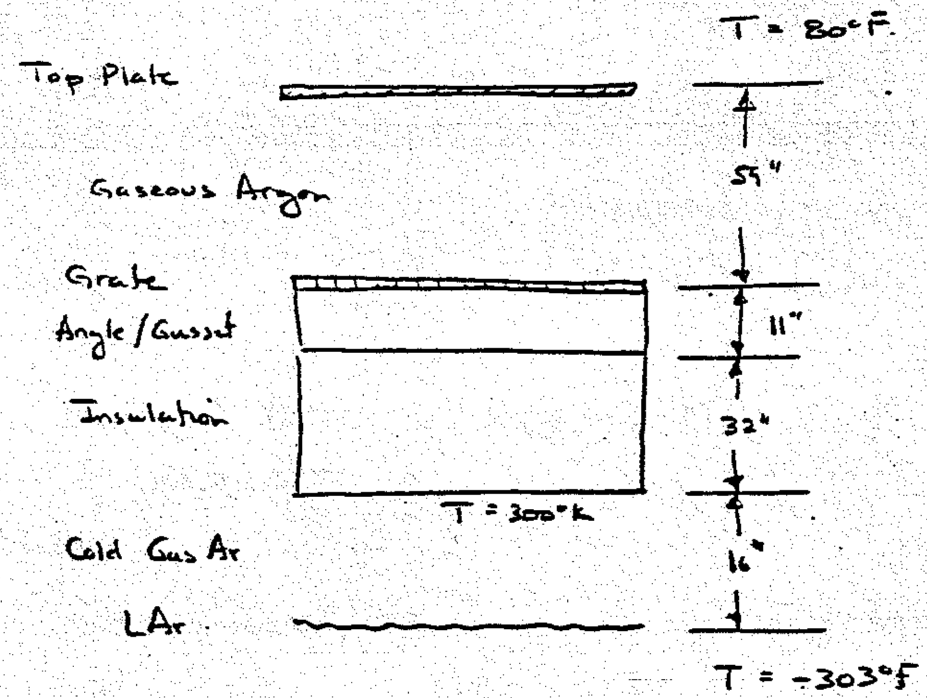
$$A = \pi D t = \pi(17)\left(\frac{0.5625}{12}\right) = 2.50 \text{ ft}^2$$

$$q_2 = \frac{A}{x}\int k\Delta T = \frac{2.50}{55}(2737) = 1246 \text{ Btu/hr}$$
$$= 346 \text{ watts}$$

$$\frac{\text{watt}}{\text{cm}} = \frac{J}{\text{sec}\cdot\text{cm}} \qquad .0009486\frac{\text{Btu}}{J} \times \frac{\text{cm}}{.03281\text{ ft}} \times \frac{3600\text{ sec}}{\text{hr.}} = 104.08.$$

$$\text{W/cm} \times 104.08 = \text{Btu/hr}\cdot\text{ft.}$$

3) Heat leak through top plate and insulation.



$$k = 0.0071 \frac{\text{BTU}}{\text{hr}\cdot\text{ft}\cdot{}^\circ\text{F}} \quad \text{for argon gas (avg)}$$

$$A = \pi \frac{D^2}{4} = \pi \frac{(17)^2}{4} = 227 \text{ ft}^2$$

$$q_3 = \frac{kA}{x} \Delta T = \frac{0.0071(227)(383)}{(59+11+32)/12} = 72.6 \text{ Btu/hr}$$

$$= 21.3 \text{ watts.}$$

4) Heat leak through rods

4 - 3½" rods ; 4 - 2" rods.

$$\int_{80\text{k}}^{300\text{k}} k \, dT = 2737 \text{ Btu/hr}\cdot\text{ft}.$$

$$A_{3\frac{1}{2}''} = \frac{\pi}{4}\left(\frac{3.5}{12}\right)^2 = 0.0668\ ft^2$$

$$A_{2\frac{1}{2}''} = \frac{\pi}{4}\left(\frac{2}{12}\right)^2 = 0.0218\ ft^2$$

$$A_T = 0.0886\ ft^2$$

$$X_{rods} = 9.5\ ft.$$

$$q_r = \frac{2737(0.0886)}{9.5} = 25.5\ Btu/hr$$

$$= 7.5\ \text{watts.}$$

Vent Line — 6 in sch 5s × .109 wall

ID = 6.407 OD = 6.625

$$A = \frac{\pi}{4}\left(\frac{6.625^2 - 6.407^2}{144}\right) = 0.0155\ ft^2$$

$$L = 9.5\ ft.$$

$$q = \frac{2737(0.0155)}{9.5} = 4.5\ Btu/hr$$

$$= 1.3\ \text{watts}$$

<u>SUMMARY</u>

	Btu/h	watts
1)	4589	1345
2)	1246	346
3)	73	21
4)	30	9
	5938	1721

$$\text{Boil off} = \frac{5938}{69.6} = 85.3\ lb/hr. = 28.3\ \text{liters/hr.}$$

#3) Heat Leak at the Top of the Tank.

Top plate:

Diameter	17.0 ft	
Thickness	0.0938 ft	($1\frac{1}{8}$")
Volume	21.3 ft^3	
Mass	10,220 lbs	@ 480 lbs/ft^3

Warm Vapor Space = 59"

Insulation 32" + 11" (between support gussets) = 43"

Fiberglass insulation.

$$K_a = \frac{k_g}{1-r}$$ where r = solid vol./total volume.

T		K
°F	°R	Btu/hr·ft·°F
-302.9	157.1	0.00350

Look at heat leak under steady state conditions from -303°F to ambient. Top plate is at ambient.

VENT PIPE

Assume:

$q_{\text{Heat Leak}}$ = 160,000 Btu/hr. above steady state

Calc. size of vent pipe (≈ 6" ID)
include velocity head + ΔP_f = Total ΔP.

Set ΔP = 5 psi i.e. pressure relief at 5 psig.

Calc. time to arrive at 5 psig assuming top 2 ft of liquid equilibrates at 5 psig.

1.) Calc. Time, t, required to equilibrate top 2 ft of LAr at 5 psig.

h_{LAr} @ 14.7 psia = 2973 j/mole
h_{LAr} @ 22.1 psia = 3160 j/mole
h_{LAr} @ 19.7 psia = 3098 j/mole

$$\Delta h = 125 \frac{j}{gmole} \times 9.486\times10^{-4} \frac{Btu}{j} \times \frac{454\,gm}{lb} \times \frac{lbm}{40\,lbs} = 1.346 \frac{Btu}{lb}$$

Vol. of LAr = $\pi DL = \pi(17\,ft)(2.0\,ft) = 106.8\ ft^3$

$$\rho = 34.27 \frac{gmmole}{liter} \times \frac{lb}{454\,gm} \times 40 \times \frac{28.32\,l}{ft^3} = 85.5\ lbs/ft^3$$ @ 1.5 atm

$$q = 106.8\,ft^3 \times 85.5 \frac{lbs}{ft^3} \times 1.346 \frac{Btu}{lb} = 12{,}291\ Btu.$$

$$t = \frac{12{,}291}{160{,}000} = 0.077\ hrs = 4.6\ minutes$$

~~Reference~~ $\Delta h_{vap} = 9499 - 3160 = 6339$ J/gmole

A 5 psig, $\Delta H_{\substack{vaporization \\ Argon}} = 6469 - (6469-6339)^2/_3 = 6382$ J/gmole.

~~68.72 Btu/lb~~

$= \frac{6382}{1055} \times \frac{454 g}{lb} \times \frac{lbm}{40 lbs} = 68.66$ Btu/lb.

LAr Vaporized $= \frac{160,000}{68.66} \times \frac{hr}{60min} = 38.84$ lbs/min

@1.5atm $\rho^{c}_{vapor} = .2095 \frac{gmole}{liter} \times \frac{lb.}{454gm} \times \frac{40 lbs}{lbm} \times \frac{28.32 l}{ft^3} = 0.523$ lbs/ft³ cold.

@1.0atm $\rho^{H}_{vapor} = 0.1034 \times \frac{19.7}{14.7} = 0.138$ lbs/ft³ (warm, 100°F, vapor) APCI Data

@1.5atm $= 0.1551$ lbs/ft³

Initially, vapor will warm as the vent pipe is cooled, ie, worst case if vapor is warm.

Vel. head Loss into and out of pipe
Frictional Loss in pipe } ΔP_T

Flow rate = 38.9 lbs/min = 2330 lbs/hr

ρ_{Ar} (warm) = 0.152 lbs/ft³ = 0.061 gm/liter (Arlab book)

PRESSURE DROP

Trial #1, d = 6.407" A = .0224 ft²

G = 10,407 lbs/hr·ft²

$V = \frac{10,407}{0.152} \times \frac{hr}{3600sec} = 19.0$ ft/sec

$\Delta P_{Head} = \frac{\rho V^2}{288 g_c} = \frac{0.152(19.0)^2}{288(32.2)} = 0.006$ psi friction

$$\Delta P/L = \frac{f\,(G')^2}{193\,\rho\, d}$$

$$N_{Re} = \frac{DG}{\mu} = \frac{\left(\frac{6.407}{12}\right)(10,407)}{.0548}$$

μ (Scotts, pg 638)

$\mu_{540} = 0.0548 \ \frac{lbs}{ft \cdot hr}$

$\mu_{157} = 0.0200 \ \frac{lbs}{ft \cdot hr}$

$$N_{Re} = 101,395$$

$$f = 0.00459$$

$$\Delta P/L = \frac{0.00459\,(2.89)^2}{193\,(0.152)(6.407)} = 0.000204 \text{ psi/ft.}$$

Trial # 2 $\quad d = 4.334 \text{ in} = 0.361 \text{ ft}^2 \qquad A = 0.102 \text{ ft}^2$

$$G = 2330/0.102 = 22,843 \text{ lbs/hr}\cdot\text{ft}^2$$

$$V_{max} = \frac{22,843}{0.152} \times \frac{hr}{3600 \text{ sec}} = 41.75 \text{ ft/sec}$$

$$\Delta P_{Head} = \frac{(0.152)(41.75)^2}{288\,(32.2)} = 0.0286 \text{ psi/head.}$$

$$Re = \frac{0.361\,(22843)}{.0548} = 150,480 \qquad f = 0.00424$$

$$\Delta P/L = \frac{0.00424\,(6.345)^2}{193\,(0.152)(4.334)} = 0.00134 \text{ psi/ft.}$$

<u>Vent pipe</u> / <u>TOP PLATE</u>

6" sch 5 $\quad t = 0.109$ inches

$OD = 6\tfrac{5}{8}" = 6.625" = 0.552\ ft$

top plate $= 1\tfrac{1}{8}"$ thick $= 1.125" = 0.0104\ ft = L$

$$A = \pi D L = \pi(0.552)(0.0104) = 0.018\ ft^2$$

$$q = 0.00991\ \frac{Btu}{ft \cdot hr \cdot {}^\circ F}\ \frac{(0.018\ ft^2)(80+303)}{(1.0/12)\ ft} = 0.82\ Btu/hr$$

Heat transfer from the plate to vent pipe assuming 40°F at top plate / insulation interface

let $q = 1.0$ Btu/hr required

$A = \pi(0.552)(0.0104) = 0.018\ ft^2$

$k_{carbon\ steel} = 360\ Btu/hr \cdot ft^2 \cdot {}^\circ F/in$ $\quad$ Perry's 23-31

$$L = \frac{kA\Delta T}{q} = \frac{360\ Btu \cdot in}{hr \cdot ft^2 \cdot {}^\circ F} \times \frac{0.018\ ft^2 \times (80-40)\ {}^\circ F}{1.0\ Btu/hr}$$

$= 259$ inches

POWER FAILURE

Power Failure or mechanical failure while gantry and moving and dewar is filled with LAr. Will sloshing be a problem?

Max. gantry speed = 6 inches/min. (per CH, 3/28/84)

Wt. Liquid = 210,000 lbsm = 462,970 kg.

Velocity = 0.5 ft/min = 0.0083 ft/sec
= 0.253 cm/sec.

$$KE = \frac{1}{2} m V^2$$
$$= \frac{1}{2}(210{,}000\,\text{lbm})\left(0.0083\,\frac{\text{ft}}{\text{sec}}\right)^2 = 7.23\ \text{lbm}\,\frac{\text{ft}^2}{\text{sec}^2}$$

$$PE = mgh$$

$$h = 7.23\,\text{lbm}\,\frac{\text{ft}^2}{\text{sec}^2} \times \frac{1}{210{,}000\,\text{lbm}} \times \frac{\text{sec}^2}{32.2\,\text{ft}} = 1.1 \times 10^{-6}\ \text{ft}$$

$$F_s = \frac{1}{2}\rho V^2 = \frac{1}{2}\left(1.4\,\frac{\text{gm}}{\text{cc}}\right)\left(0.253\,\frac{\text{cm}}{\text{sec}}\right)^2 = 0.0448\ \text{gm}\,\frac{\text{cm}}{\text{sec}^2}/\text{cm}^2$$

$= 0.0448$ dynes/cm^2
$= 4.57 \times 10^{-5}$ cm H_2O
$= 3.27 \times 10^{-5}$ cm Argon

Insignificant ..

$1 \times 10^6\ \frac{\text{dynes}}{\text{cm}^2} = 1020.5$ cm H_2O

TRANSFER LINE FAILURE

Flowrate — 100 gpm of LAr = 68,564 lbs/hr.
(ρ = 85.5 lbs/ft^3 · 11.42 lbs/gal.)

Calculate transfer line size
Trial #1 ; $1\frac{1}{2}$" IPS Sch 5 I.D. = 1.77 inches
= 0.1475 ft.

$$A = 0.0171 \text{ ft}^2$$

$$G = \frac{68{,}564}{0.0171} = 4.013 \times 10^{+6} \text{ lbs/hr·ft}^2$$

μ = 0.531 lbm/ft·hr. Barron Pg. 635

$$N_{Re} = \frac{0.1475(4.013\times10^{+6})}{0.531} = 1.11\times10^{+6} \qquad f = .00284$$

$$\frac{\Delta P}{L} = \frac{0.00284\left(4.013\times10^{+6}/3600\right)^2}{193\,(85.5)(1.77)} = 0.1208 \text{ psi/ft.}$$

In 100 ft ΔP = 12.1 psi high

Trial #2 2" IPS Sch 5 I.D. = 2.245 in
= 0.1871 ft.

$$A = 0.0275 \text{ ft}^2$$

$$N_{Re} = \frac{0.1871(2.493\times10^{6})}{0.531} = 8.785\times10^{5} \qquad f = .00298$$

$$\Delta P/L = \frac{0.00298 \left(2.493\times10^6/3600\right)^2}{193\,(85.5)(2.245)} = 0.0386/ft.$$

For 100 ft, $\Delta P = 3.86$ psi <u>Ok.</u>

Use 2" IPS Sch 5 tranfer Line.

2" Cryolab globe valve, $C_v = 50$

$$C_v = \frac{gpm\sqrt{Sp.Gr}}{\sqrt{\Delta P}} \qquad Sp.Gr = \frac{85.5}{62.4} = 1.37$$

Upstream of the pump, $\Delta P = 10$ psi (Stg. tank minus ΔP_f)

$$GPM = \frac{C_v(\Delta P)^{1/2}}{(Sp.Gr)^{1/2}} = \frac{50\,(10)^{1/2}}{(1.37)^{1/2}} = 148.3$$

Discharge from the pump, $\Delta P = 30 - 14.7 = 15$ psi
100 gpm @ 50 ft Argon.

$$P_D = \frac{50\times85.5}{144} = 29.7\ psig$$

$$GPM = \frac{50\,(15)^{1/2}}{(1.37)^{1/2}} = 165\ gpm.$$

LAR DEWAR OVERFILL

Pump: Rated at 100 gallons/min. LAr.

210,000 lbs = 18,372 gallons/fill

time to fill = 183.72 min = 3.1 hrs.

Void Volume above liquid level and Insulation barrier

$h = 16'' = 1.33\ ft.$

$Vol = \pi \frac{D^2}{4}(h) = \pi \frac{(17)^2}{4}(1.33)(7.48) = 2258$ gals.

time to fill this vol. = 22.6 minutes

Vol/ft = 1694 gals.

t = 17 min / ft

#2) What if: Insulation disappears, then N_2 insulation shield of is lost.

K_{N_2} @ -300°F = 0.00501 Btu/ft·hr·°R
K_{N_2} @ 70°F = 0.0148 Btu/ft·hr·°R
K_{N_2} (average) = 0.00991 Btu/ft·hr·°R

Heat Leak to the Shell with 12" fiberglass insulation, equivalent to 12" N_2 gas insulation

$$q = \frac{KA\Delta T}{t} = \frac{0.00991(1.0\,ft^2)(70+303)}{1.0\,ft} = 3.696\ \frac{Btu}{hr\cdot ft^2}$$

$\Delta h_{vap.}$ Argon = 70 Btu/lb.

From Cryogenic Data Book, Chelton & Mann, UCRL-342
Date - Unknown, 1950's.

• At ΔT = 20°K

$$Q = 1.15\ watts/cm^2 = 1.15\ \frac{joules}{cm^2\cdot sec}$$

∴

$$h = \frac{Q}{\Delta T} = .0575\ \frac{joules}{sec\cdot cm^2\cdot °K}$$

To convert to engineering units

$$\frac{Joules}{Sec\cdot cm^2\cdot °K} \times \frac{1.8\,°K}{°R} \times \frac{3600\,sec}{hr} \times \frac{cm^2}{1.076\times10^{-3}\,ft^2} \times 9.486\times10^{-4}\ \frac{Btu}{Joules}$$

$$\frac{Btu}{hr\cdot ft^2\cdot °R} = \frac{Joules}{cm^2\cdot sec\cdot °K} \times (5712.8)$$

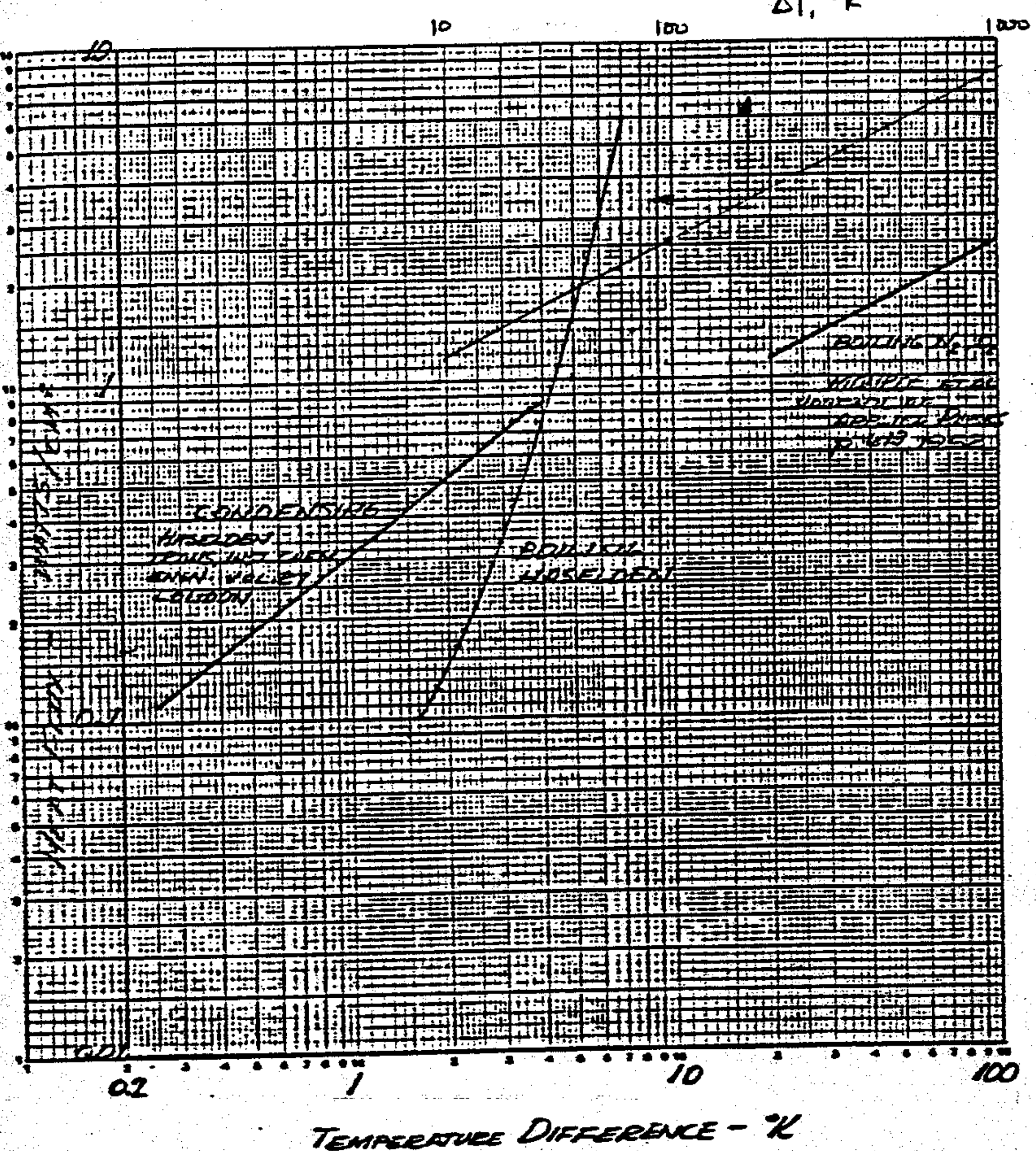
#2) Con't

BOILING N_2 - COEFFICIENTS

ΔT, °K	ΔT, °F	Heat Leak joules/sec. cm²		Individual Heat Transfer Coeff, h joules/cm². sec. °K	Individual Heat Transfer Coeff, h Btu/hr. ft². °F
1		.050	Nucleate Boiling	.050	286
2		0.195		.0975	557
3		0.340		.113	647
4		0.770		.193	1103
5		1.57		.314	1794
6		3.00		.500	2866
7		5.70		.814	4652
20		1.15	Film Boiling	.0575	328
60		1.95		.0325	186
100		2.55		.0255	146
111	200				140.0

HEAT TRANSFER TO BOILING

AND CONDENSING NITROGEN



#2) con't.

- Worst case — Complete Loss of Vapor Barrier

Ambient Temp on outside wall of the tank.

$\Delta T = 100 + 303 = 403°F$

$q = \underset{\substack{\uparrow \\ high}}{150} (1.0 ft^2)(403) = 60{,}450 \frac{BTU}{hr \cdot ft^2}$ (heat Leak)

which would vaporize, $\rho_L = 87\ lbs/ft^3 = 11.63\ lbs/$

$LAr\ vaporized = \frac{60{,}450\ BTU/hr \cdot ft^2}{70.0\ BTU/lb.} = 864\ lbs/hr \cdot ft^2$
$= 74.29\ gals/hr \cdot ft^2$

would generate,

$\rho_{vapor} = 0.1444 \frac{gmmoles}{liter}$ @ $87.3°K$, 1 atm pressure

$= 0.360\ lbs/ft^3 =$

Cu ft LAr generated / ft^2 of Lost Insulation $= \frac{864\ lbs/hr \cdot ft^2}{0.360\ lbs/ft^3} = 2400 \frac{cft^3}{hr \cdot ft^2}$ of surf area

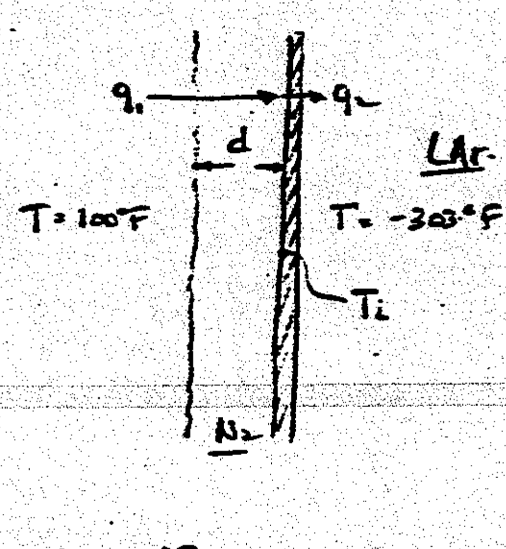
- Suppose vapor barrier reduced from 1.0 ft to 1.0 inch = d

If $T_i = -100°F$

Then heat leak through N_2

$q_1 = 0.0124 \frac{(1.0 ft^2)(100 - (-100))}{1/12}$

$= 29.8\ BTU/hr \cdot ft^2$



$k_{-100°F} = 0.00791$

$k_{Ave} = 0.0124$ from $+100°F \rightarrow -100°F$

#2 con't)

$\Delta T = -200°F = 111.1°K$ $\qquad h_{N_2} = 140\ Btu/hr \cdot ft^2 \cdot °F$

$$q_2 = 140(1.0)(200) = 28{,}000\ Btu/hr \cdot ft^2$$

$\therefore$ N_2 barrier is controling, i.e. T_i will be much lower than $-100°F$

If $T_i = -300°F$

Then

$$q_1 = \frac{0.00991\,(1.0)(100-(-300))}{1/12} = 47.6\ Btu/hr \cdot ft^2$$

$$q_2 = 557\,(1.0)(3°F) = 1671\ Btu/hr \cdot ft^2$$ $\qquad \Delta T = 3°F = 1.7°K$

Vapor barrier heat transfer rate still controlling
Nucleate boiling.

- At what vapor (N_2) thickness would $q_1 = q_2 = 1671\ \frac{Btu}{hr \cdot ft^2}$

$$t = \frac{0.00991\,(1.0)(400)}{1671} = 0.00237\ ft = \underline{0.03\ inches}$$

$= 0.7\ mm$ Thick

#2 con't)

• Surface Area of vessel (insulated)

224" equals blank to make head

$$A_{Dish} = \frac{\pi d^2}{4} = \frac{\pi}{4}\left(\frac{224}{12}\right)^2 = 274\ ft^2$$

$$A_{circumference} = \pi d L = \pi(17\ ft)(17.5\ ft) = 935\ ft^2$$

Total Surface Area = 1209 ft^2

• At $q = 2000\ Btu/hr \cdot ft^2$

$$LAr\ Vaporized = \frac{2000\ Btu}{hr \cdot ft^2} \times \frac{lb}{70\ Btu} \times \frac{ft^3}{0.360\ lbs} = 79.4\ \frac{acfh}{ft_s^2}$$

If velocity of sound is say 500 ft/sec.

$$Vent\ area\ req'd = 79.4 \frac{ft^3}{hr \cdot ft_s^2} \times \frac{sec}{500\ ft} \times \frac{hr}{3600\ sec} = 4.41 \times 10^{-5} \frac{ft^2}{ft_s^2}$$

for 10% loss of insulation, $ft_s^2 = 120.9\ ft^2$

$$A_{vent} = 4.41 \times 10^{-5} \frac{ft^2}{ft_s^2} \times 120.9\ ft_s^2 = 5.33 \times 10^{-3}\ ft^2$$

ID Pipe = 0.959 inch. $\quad D = \left[A\left(\frac{4}{\pi}\right)\right]^{1/2}$

for 50% loss of insulation, $ft_s^2 = 604.5\ ft^2$

$$A_{vent.} = 4.41\times10^{-5}\ \frac{ft^2}{ft_s^2} \times 604.5\ ft_s^2 = 2.666\times10^{-2}$$

$$ID_{vent} = 2.21 \text{ inches}$$

VELOCITY OF SOUND

CRC- 56th Edition E-47

Argon - Velocity of sound @ 0°C = 319 m/sec (1047 ft/sec)

$\Delta V/\Delta T$ = 0.56 m/sec·°C

N_2 - Velocity of sound @ 0°C = 334 m/sec (1096 ft/sec)

$\Delta V/\Delta T$ = 0.60 m/sec·°C

O_2 - Velocity of sound @ 0°C = 316 m/sec (1037 ft/sec)

$\Delta V/\Delta T$ = 0.56 m/sec.

Let ΔT = 300°F = 166.7°C

ΔV = 166.7 (0.56) = 93.4 m/sec (306.3 ft/sec)

Argon V = 740.7 ft/sec @ -300°F

too high, use velocity of sound of Oxygen.

Vel Sound O_2 @ -183.3°C = 583 ft/sec

-298°F

Flat Plate Cooling

$$Y_s = \frac{t_a - t_s}{t_a - t_b}$$

t_a = temp surroundings -303°F
t_b = Solid Orig temp, 80°F
t_s = temp at surface

$$X = \frac{k\theta}{\rho C_p r_m^2}$$

k = Thermal Conductivity, 1.0 Btu/hr·ft·°F
ρ = density, 144 lbs/ft³ (cement)
C_p = Specific heat, 0.16 Btu/lb °F (cement)
r_m = normal distance from midplane to surface, ft.

$$m = \frac{k}{h x}$$

h = heat Transfer coeff to surroundings. ~ 300 Btu/hr·ft²·°F
x = Normal distance from surface to pt, ft.

Use chart pg. 39
t = Temp at position x at time θ.

$\alpha = k/\rho C_p$, where $m = \frac{1.0}{300 \times 0.08} = 0.04 \sim 0$

for x = 1.0 inch, figure 3-6 is ok

$$\alpha = \frac{1.0 \text{ Btu/hr·ft·°F}}{144 \text{ lbs/ft}^3 \cdot 0.156 \text{ Btu/lb·°F}} = 0.0445 \text{ ft}^2\text{/hr}$$

α ~ Thermal Diffusivity

$\alpha = .0445\ ft^2/hr.$

$$Z = \frac{x}{(4\alpha\theta)^{1/2}} \qquad Y = \frac{t_a - t}{t_a - t_b} = \frac{-303 - t}{-303 - 80}$$

$$Z = \frac{x}{0.4219\,\theta^{1/2}} \qquad = \frac{-303 - t}{-383}$$

$$(4\alpha)^{1/2} = 0.4219 \qquad -383\,Y = -303 - t$$

$$t = +383\,Y - 303$$

Using Chart Fig 3-6 McAdams, Pg. 39

θ		X		Z	Y	t
min	hrs	in	ft	-	-	°F
1.0	0.0167	1.0	0.083	1.52	0.95	61
1.0	0.0167	2.0	0.166	3.04	1.00	80
0.1	.00167	0.1	0.0083	0.48	0.51	-108
0.1	.00167	1.0	0.0833	4.83	1.00	80
0.5	.00833	0.5	.0417	1.08	0.87	30.2

$$q = \frac{kA\,\Delta T}{x} = \frac{1.0\,(800)(383)}{x} = \frac{0.3064 \times 10^6}{x}\ \frac{Btu}{hr}$$

$$G = \frac{q}{\Delta h_{vap}\ \rho_{air}} = \frac{12159}{x}\ acfh$$

Let $Z = 2.00$, $Y = 0.9953 \sim 1.00$

Rearranging $Z = \dfrac{X}{0.4219\,\theta^{1/2}}$ and let $Z = 2.0$

$$\theta^{1/2} = \frac{X}{0.8438} \quad (\text{hrs})$$

$$\theta = 1.404\,X^2 \quad (\text{hrs})$$

Progress of cooling wave into the concrete, ie X = interface
@ T = 80°F

X		θ	q				V
in	ft	min	Btu/hr	acf/hr	lbs/hr		ft/sec
0.01	.00083	5.50×10^{-5}	—	1.46×10^{7}	5.27×10^{6}		
0.1	.0083	5.80×10^{-3}				1937	
0.5	.0166	2.32×10^{-2}		732,970	263690	1478	
1.0	.083	0.580		152,000	54720	1176	7.3
2.0	.166	2.32		73,247	26369	1062	
3.0	.249	5.22		48,831	17579	1069	
4.0	.332	9.39		36,623	13184	1011	
5.0	.415	14.5		29,299	10548	34231	
24.0	2.0	337.0		6,080	2189		

$A_{\text{cross section}} = \frac{\pi}{4}(21)^2 = 346\ \text{ft}^2$

Concrete Pit

$A = 800$

$K_{concrete} = 1$ Btu/ft hr °F $= 12$ Btu/hr in °F

$Q = 800 \times 12 \times 400 = 3.84 \times 10^6$ Btu/hr
9600 / 70

70 Btu/lb

55000 lbs/hr / 1.36

2500 ft/hr

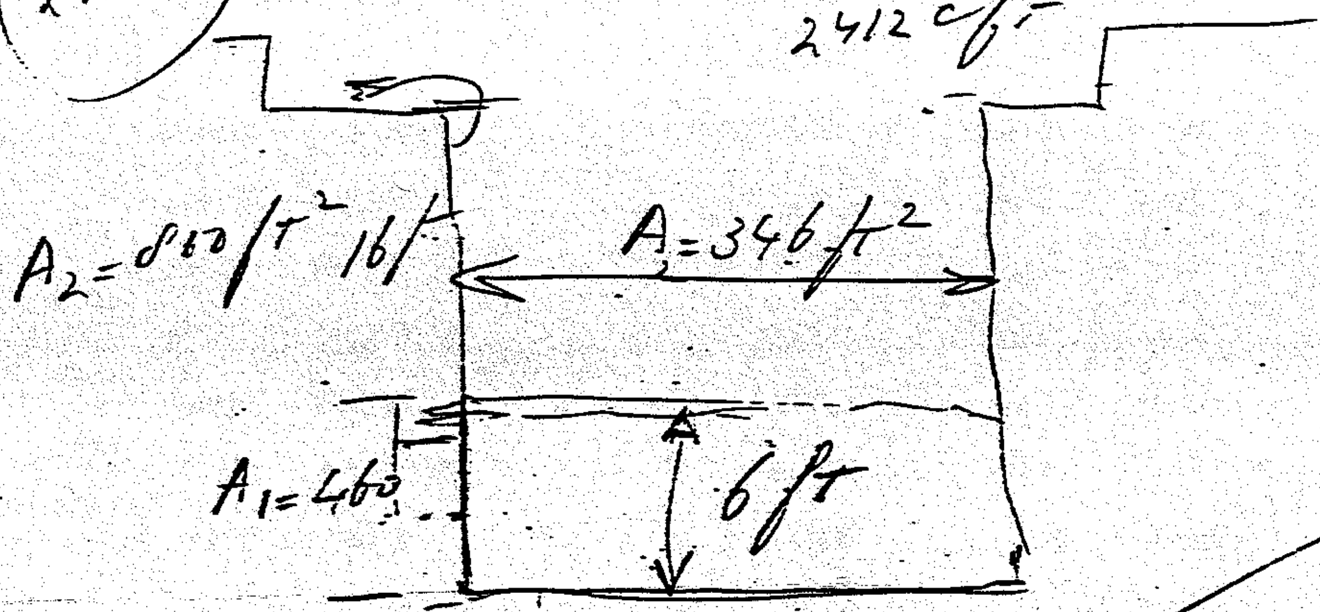
.75 ft/hr

5800 ft

150,000 ft/hr / 60

2 min

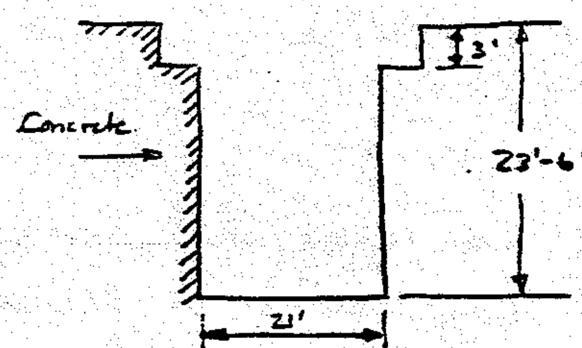
210,000 lbs
2412 cfs



How fast does gas exit the pit?

Bldg inventory

1) What If: LAr tank developes a leak and LAr drops into the concrete pit. Concrete is at ambient temperature, say 300°K and LAr is at liquifaction temperature, say 87.3°K (1 atm)



$\rho = 142 \text{ lbs/ft}^3$

$C_p = 0.156 \text{ Btu/lb}\cdot°F \; (32°F - 212°F)$

$K_{concrete} = 1.05 \frac{\text{Btu}\cdot\text{ft}}{\text{ft}^2\cdot\text{hr}\cdot°F}$ @ 75°F

Coeff of expansion $= 0.08 \times 10^{-4}/°F$ (avg. 32°F → 212°F)
6×10^{-6} (another source)

Argon in vessel = 210,000 lbs = 2412 ft³

$\rho = 34.89 \frac{\text{gmole}}{\text{liter}} \times \frac{\text{lb}}{454 \text{gm}} \times \frac{40 \text{lbs}}{\text{lbm}} \times 28.32 \frac{\text{l}}{\text{ft}^3} = 87.06 \text{ lbs/ft}^3$

How much of pit would be filled?

$$2412 \text{ ft}^3 = \frac{\pi D^2}{4}(L)$$

$$L = \frac{2412(4)}{\pi D^2} = 6.96 \text{ ft}$$

A (surface area for heat transfer) = $\pi D L$

$= \pi (21)(6.96) = 459.2\ ft^2$

Δh_{vap} (LAr) = $(9442 - 2973)$ j/gmole = 6469 j/gmole.

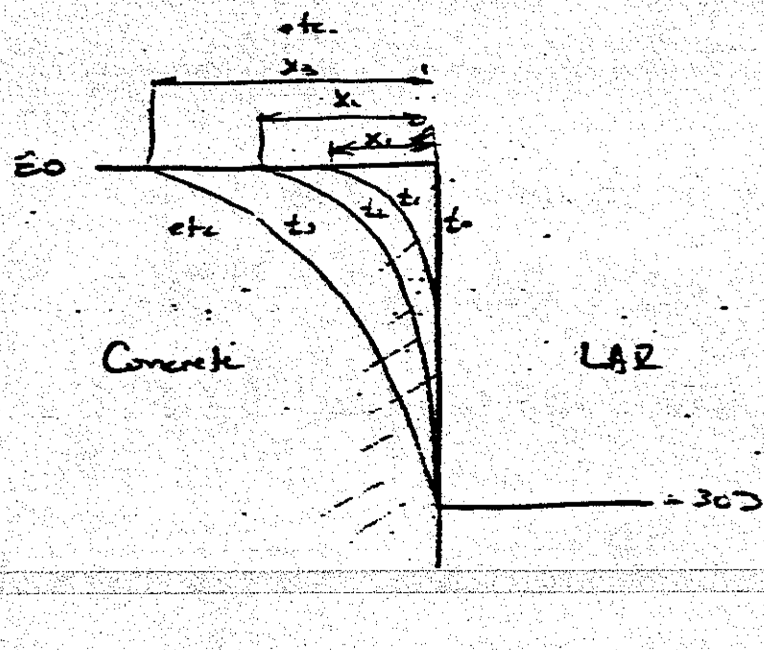
$= 6469 \frac{j}{gmole} \times 9.486 \times 10^{-4} \frac{Btu}{j} \times 454 \frac{gm}{lb} \times \frac{lbm}{40\ lbs} = 69.6$ Btu/lb

(APCI − Δh_{vap} = $2804 \frac{Btu}{lbm}$ = 70.1 Btu/lb.)

Mechanism, will have argon boiling at the wall of the pit with heat being removed as follows:

$$q_T = \frac{kA(T_1 - T_2)}{X} \quad \text{, at some time, } t.$$

Then q_T must be transferred to boiling liquid.



Temp. curves in concrete.

3/15/84
Pg. 3
584

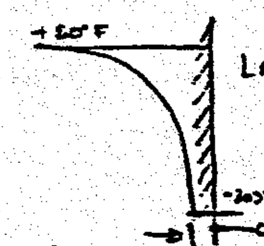
A) at $X = 0$ $\qquad q_T = \infty$ $\qquad \Delta T = 80 + 303 = 383°$

$A = 459\ ft^2$

$t_1 : X = 0.1$ in $\qquad q = \frac{(12.6)(459)(383)}{0.1} = 2.22 \times 10^8$ Btu/hr.

t_2 $\quad x = 0.5$ in $\qquad q = 4.43 \times 10^7$

t_3 $\quad x = 1.0$ in $\qquad q = 2.22 \times 10^7$



B) How long to bring frost $X = 0.1"$ to $-303°F$

$$q = m C_p \Delta T = (459\ ft^2)\left(\frac{0.1}{12}\right)\left(142\ \frac{lb}{ft^3}\right)(0.156)(80+303)$$

$$= 3.25 \times 10^5 \text{ Btu/hr.}$$

C) How many Btu vap. in 210,000 # LAr?

$$Q_{vap} = 69.6\ \frac{Btu}{lb}\,(210{,}000) = 1.46 \times 10^7 \text{ Btu} \quad \text{(TOTAL)}$$

Calculate rate of increase in vapor/liquid level in pit for maximum vaporization.

ρ_L = 87 lbs/ft^3
ρ_{vapor} = 0.36 lbs/ft^3
Crossectional Area = $\pi \frac{(21)^2}{4}$ = 346 ft^2

ΔVol/hr = 152,000 acf/hr − 152,000 × $\frac{0.36}{87.0}$

= 151,370 acf/hr

Δh/hr = $\frac{151,370 \text{ ft}^3/\text{hr}}{346 \text{ ft}^3/\text{ft}}$ = 437 ft/hr = 7.3 ft/min

h_T avail = 23.5 ft − 7.0 ft = 16.5 ft.
t, to fill pit/gas/liq = $\frac{16.5}{7.3}$ = 2.3 minutes

How long to boil off all of the liquid at max. rate?
Heat transfer rate = $\frac{1.0 (800)(383)}{0.08}$ = 3.83 × 10^6 Btu/hr

t = $\frac{210,000 \text{ lbs} \times 70 \text{ Btu/lb}}{3.83 \times 10^6 \text{ Btu/hr}}$ = 0.261 hrs = 15.6 min

Initial Vapor volume above liquid = $\pi \frac{(21)^2}{4}(23.5-7)$ = 5715 ft^3

Calc coefficient - for boiling LAr with assumption $q = 3.83 \times 10^6$ Btu/hr.

If $q = 3.83 \times 10^6$ Btu/hr.
$A = 800\ ft^2$
$\Delta T = 3\,°F$
} Boiling Coeff

$$h_{calc} = \frac{3.83 \times 10^6}{800 \times 3} = 1596\ Btu/hr \cdot ft^2 \cdot °F$$

Corresponds to nucleate boiling at 4° F.

If $\Delta T = 20°F$ under same conditions
$h_{calc} = 239\ Btu/hr \cdot ft^2 \cdot °F$ About right.

Back calc. value of X for concrete

$$X = \frac{k A \Delta T}{q} = \frac{1.0\,(800)(383-20)}{3.83 \times 10^6} = 0.076\ ft$$
$= 0.91$ inches.